A review of tennis racket performance parameters

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Abstract

The application of advanced engineering to tennis racket design has influenced the nature of the sport. As a result, the International Tennis Federation has established rules to limit performance, with the aim of protecting the nature of the game. This paper illustrates how changes to the racket affect the racket-player system. The review integrates engineering and biomechanical issues related to tennis racket performance, covering the biomechanical characteristics of tennis strokes, tennis racket performance, the effect of racket parameters on ball rebound and biomechanical interactions. Racket properties influence the rebound of the ball. Ball rebound speed increases with frame stiffness and as string tension decreases. Reducing inter-string contacting forces increases rebound topspin. Historical trends and predictive modelling indicate swingweights of around 0.030 to 0.0350 kg/m^2 are best for high ball speed and accuracy. To fully understand the effect of their design changes, engineers should use impact conditions in their experiments, or models, which reflect those of actual tennis strokes. Sports engineers therefore benefit from working closely with biomechanists to ensure realistic impact conditions.

1. INTRODUCTION

Sports equipment manufacturers continually strive to improve their products in a competitive marketplace. Improvements in tennis racket design, testing and manufacturing have influenced the nature of the sport. Simulations have predicted that a player could serve 18% faster with modern equipment compared to what was available in the 1870s [1].

Major changes in racket design occurred in the 1970s, when engineers started experimenting with new frame shapes and geometries, utilising materials such as aluminium and composites in place of wood (see [1–3] for a detailed description). The oversize head pioneered by Howard Head [4] and other design changes like longer and “widebody” rackets contributed towards substantially faster ball rebounds. The design prompted the International Tennis Federation (ITF) to establish limits on the dimensions of rackets in 1981; currently set at 29.0 inches (73.7 cm) for overall length, 15.5 inches (39.4 cm) for strung surface length, 12.5 inches (31.7 cm) for overall width and 11.5 inches (29.2 cm) for strung surface width [5, 6]. To protect the nature of the game the ITF tests equipment and establishes rules to limit performance. The rules still allow for significant variability in stiffness, inertia (mass and balance) and string bed properties to influence the specific playing characteristics of each racket.

Many investigations into tennis racket performance have tended to focus on the racket in isolation without considering how it will be used by the player. For example, the majority of physical testing of racket performance has focused on impacts normal to the racket face, which is not representative of actual tennis strokes and recent work has shown that impact angles deviate from normal to the racket face by up to 33° [7]. Few studies have attempted to determine the effect of racket parameters on a groundstroke using impact conditions consistent with advanced play. Despite this there is considerable research into tennis biomechanics which has sought to understand the motion and methods of power generation of the tennis player.

While focusing on the racket, this paper reviews research that considers all elements of the racket-player system and attempts to illustrate how changes in racket parameters affect this system. The review integrates engineering and biomechanical issues related to tennis racket performance. For example, changes in the moment of inertia about the grip of the racket affect not only the ball/racket interaction, but how quickly a player is able to swing it [8]. Early sections cover the biomechanics of tennis strokes and racket performance characterisation techniques. The main body of the paper focuses on the effect of racket parameters (e.g., inertia, stiffness and string bed properties) and the effect of these parameters on player performance in tennis strokes. While there are several other reviews of the research on tennis equipment [2, 6, 9–12], this paper considers how changes to the racket affect the racket-player system.

2. BIOMECHANICAL CHARACTERISTICS OF TENNIS STROKES

The biomechanical parameters of most tennis strokes have been studied extensively, primarily in laboratory/court simulated conditions. Extensive reviews of tennis biomechanics research have been published [12–14]. This section will summarise several consistent observations of biomechanical studies across the main strokes (ground strokes and serve) primarily in samples of advanced and elite players.

2.1. Groundstrokes

Tennis groundstrokes are ballistic striking activities that can be performed using a variety of coordination strategies – through numerous combinations of multiple body segments and multiple degrees of freedom at the joints between the segments. Early 20th century rackets were heavier with smaller hitting areas than current rackets [1] so groundstrokes tended to be more whole-body movements. However, early biomechanical studies of elite players observed both simultaneous and sequential styles of groundstroke coordination

[15]. There appears to be a continuum between simultaneous/single-unit and sequential/multi-segment coordination in tennis groundstrokes [16].

As racket and string properties have changed, ball speeds have increased and, with the associated pressure on time and court movement, more players are using open stance forehands. Many players now use open stance forehand and backhand groundstrokes with less forward weight shift and greater reliance on sequential trunk and upper extremity rotations to accelerate the racket. The variety of grip styles, kinds of groundstrokes, and complex combinations of upper extremity joint rotations make it difficult to identify stable contributions of specific segment motions to racket speed or accuracy. Grip styles [17] and even the intended stroke speed can influence segment coordination used in groundstrokes [18].

Ranges of racket trajectories and racket angles – relative to the ball – have been reported for most strokes [7, 13, 19]. Choppin et al. [6] reported pre-impact racket speeds at impact for groundstrokes of touring professionals, ranging from 17 to 36 m/s for males and 20 to 29 m/s for females. The angle between the ball and racket face normal at impact was similar for males and females, ranging from 14 to 33º. The study of these important interactions has been complicated by the short duration of impact (3 to 5 ms) and data smoothing problems related to impact [20–22]. Skilled tennis players positively accelerate the racket up to impact, reaching peak racket speed just before deceleration created by impact and follow-through. Early studies did not observe this synchronised peak in racket speed because of low sampling rates and distortions of smoothing through impact [15, 16].

2.2. The Serve

Tennis rules require the player to serve from a stationary position on the court (no approach) with the ball tossed and hit before it bounces. There is greater biomechanical consistency in serving than other strokes because of greater consistency of impact conditions and the great advantage a player has if they have developed a high-speed overhead service. In general, it is advantageous for the player to develop a high point of racket-ball impact above the court with high racket-head speeds. It is also advantageous to use a variety of racket trajectories to vary post-impact ball velocity, spin, and placement in the service box. See Knudson [13] for a complete review of the biomechanics of the tennis serve.

Players generally use two patterns of stance and a sequential coordination of the lower body, trunk, and upper extremity to create high racket speed at impact in the serve [13]. Advanced players use a continental or backhand grip to maximise the ability to use forearm and wrist rotations to create ball speed and spin. Higher spin rates have been reported for serves in comparison to groundstrokes [23, 24]; ~100 to 400 rad/s in comparison to ~0 to 350 rad/s.

Serves are commonly called flat, slice, and twist (kick) according to the principal racket trajectory, impact position, and racket angle [19, 25]. Flat serves are a misnomer; while these serves maximise ball speed, the path of the racket and angle of the racket face create topspin and side spin [26, 27]. Slice serves emphasise side spin, while twist serves emphasise top spin with some side spin [13, 19]. While many recreational players feel they hit the ball with an initial downward trajectory in the serve, this tends not to be the case, only advanced players with high-speed and spin serves can hit the ball on a slightly-downward trajectory (< 10 degrees with respect to the horizontal) [13].

3. TENNIS RACKET PERFORMANCE

The assessment of racket performance is essential in order to explore, appraise and compare design choices. Researchers and engineers typically use a combination of physical testing and mathematical modelling to assess and predict racket performance. This section will cover i) testing methodologies and ii) modelling techniques.

3.1. Testing methodologies

The laboratory test methods utilised to measure racket performance have become increasingly advanced in recent years. Bespoke tests are typically developed and applied by the ITF, researchers, and equipment manufacturers. Unlike baseball bats [28] - where safety is a concern due to the use of a solid ball - there are no standardised tests for measuring tennis racket performance. Details of some tests – typically those utilised by the ITF and independent researchers – make their way into the public domain, while those used for equipment development often remain closely guarded. Table 1 shows varying racket constraints between studies concerning oblique impacts, with impact angles often exceeding the maximum of 33° report by Choppin et al. [7] for actual tennis strokes.

Table 1 Comparison of testing methodologies (experiment and model).

Year	Author/s	Racket constraint	Impact angle to racket normal (°)
1993	Knudson [29]	hc	25
1999	Bower and Sinclair [30]	hc	45*
2003	Cross [31]	r, fc, hh	10 to 60*
2004	Goodwill and Haake [32]	fc	39*
2009	Allen et al. [33]	u	24
2010	Allen et al. [34]	u	20 & 40*
2011	Allen et al. [35]	u	20
2012	Haake et al. [36]	fc	40* & 60*
2013	Nicolaides et al. [37]	fc	26
-	ITF Spin Test	fc	40* & 60*

hc = handle-clamped, r = rollers, fc = full-constrained, hh = handheld, u = unconstrained.
*indicates angles exceeding 33°

Experiments typically involve simulating a ball/racket impact while measuring ball rebound. A tennis stroke usually involves a moving ball and racket while impact tests may keep the racket stationary. These two conditions are rendered equivalent through a change in the Newtonian frame of reference (see [38, 39]). Performance characteristics of particular relevance are: i) the coefficient of restitution (COR) of the racket/ball system, ii) rebound ball angle and iii) rebound ball spin. Coefficient of restitution is defined as the ratio of relative velocities after and before impact normal to the racket face. A simpler measure is apparent coefficient of restitution (ACOR), which directly determines ball rebound speed. ACOR is defined as the ratio of ball velocities after and before impact normal to the racket face, when the racket is initially stationary. Kotze et al. [10] and Cross [10] provide comprehensive discussions of COR.

Another key performance parameter is the 'sweet spot'. The common notion of the sweet spot is a mix of three points on the racket face [40, 41]: the area of maximum rebound ball speed, the point of minimum vibration (node), and the point of no frame reaction (centre of percussion, COP). The point of maximum rebound velocity (the 'power point') is located near a racket's centre of mass (COM) when stationary. However, during a stroke, the location of this point is dependent on the relative velocity of the ball and racket, and the racket's mass and moment of inertia [42, 43].

The node point of a racket generates minimum frame vibration when hit (Fig. 1) and is the sweet spot many players 'aim' for [7, 44]. It is unclear, however, how racket sweet spots relate to the general "feel" tennis players say they have for specific rackets. The location of the node point is dependent on the stiffness and mass distribution of the strung racket – it is also affected by the presence of the player's hand at the grip.

An impact at the COP is said to create no 'jarring' effect (Fig. 2). Assuming the racket moves as a rigid body, the distance of the COP from the centre of mass (b) is the ratio of the moment of inertia about a horizontal line passing through the COM (I_{COM}) to the product of racket mass (M) and distance from the hand (rotation point) to the centre of mass [39]. This calculation omits forces arising from the grip of the hand and COP is therefore irrelevant to actual tennis shots [45, 46]. Methods for obtaining the moment of inertia of a tennis racket can be found elsewhere [47, 48] [49].

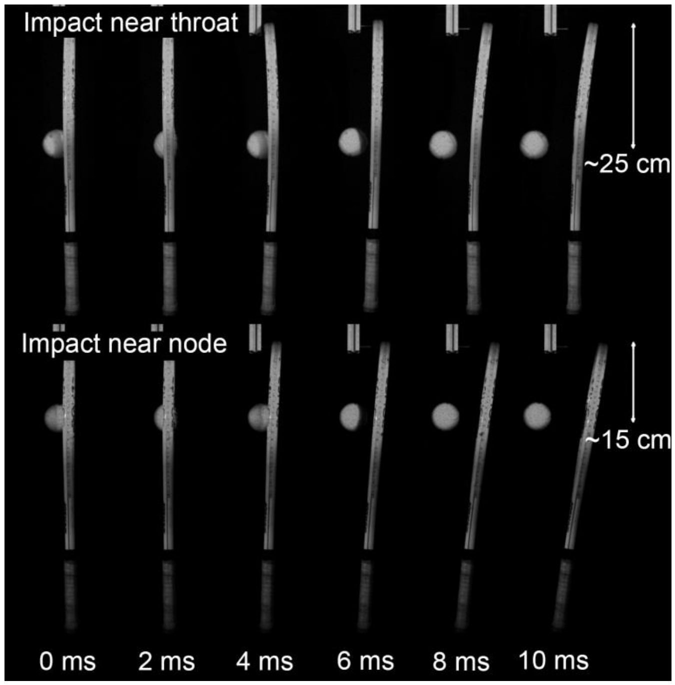

Figure 1 High-speed (shown at 500 Hz) video of the impact phase of a collision of a ball with a free racket. Ball and frame response during the 5 ms impact phase are similar to hand-held conditions during a groundstroke. The top image sequence shows considerable vibrations in the racket frame for an impact in the throat region, while the bottom image shows little frame vibrations for an impact close to the node.

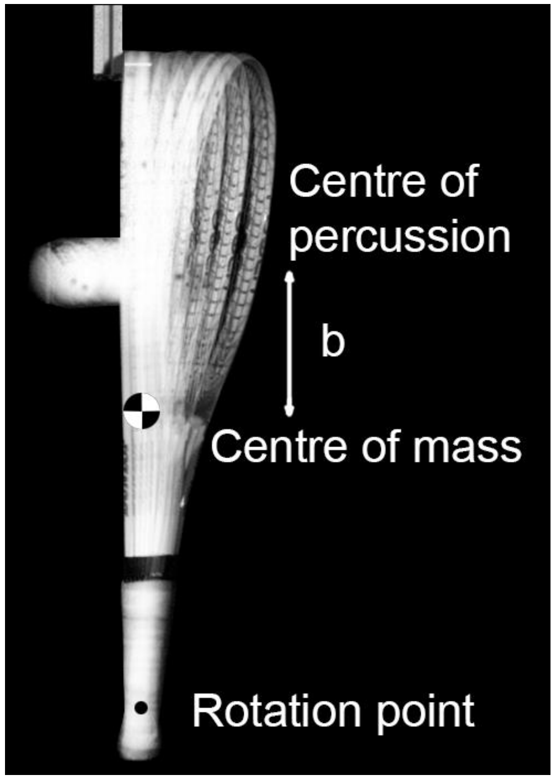

Figure 2 Superimposed high-speed video of the impact phase of a collision of a ball with a free racket. An impact at the centre of percussion results in an instantaneous centre of rotation at wrist.

Early studies focused on appropriate methods of racket support i.e. how best to accurately represent impact during a tennis stroke. A hand-held racket vibrates at a similar frequency to a freely suspended racket [41, 50], but clamping the handle significantly lowers the frequency [9]. If the ball leaves the string bed before the vibrational wave associated with the fundamental frequency mode has time to travel to the hand and back again, then handle grip has no effect on ball rebound. This has shown to be the case in the majority of impacts on the longitudinal axis [39, 41, 51, 52]. A detailed discussion of the effect of grip forces is included in section 5.2.

Unconstrained rackets (e.g. freely suspended or free standing) are preferred for impact testing; experimental setup is simpler and risk of frame damage is lower in comparison to handle-clamped. Early experimental methods often involved projecting the ball normal to the face while measuring its inbound and rebound velocity with light gates or a high-speed camera (e.g. [53, 54]) (Figure 3). The ITF uses a fully automated Racket Power Machine, as a means of characterising the performance of a large number of rackets [5]. The device simulates an impact on the longitudinal axis of the racket (clamped at the handle) by dropping a ball into its path as it is rotating about a fixed axis. Goodwill et al. [55] confirmed that the device provides comparable results to projecting a ball against a freely suspended racket.

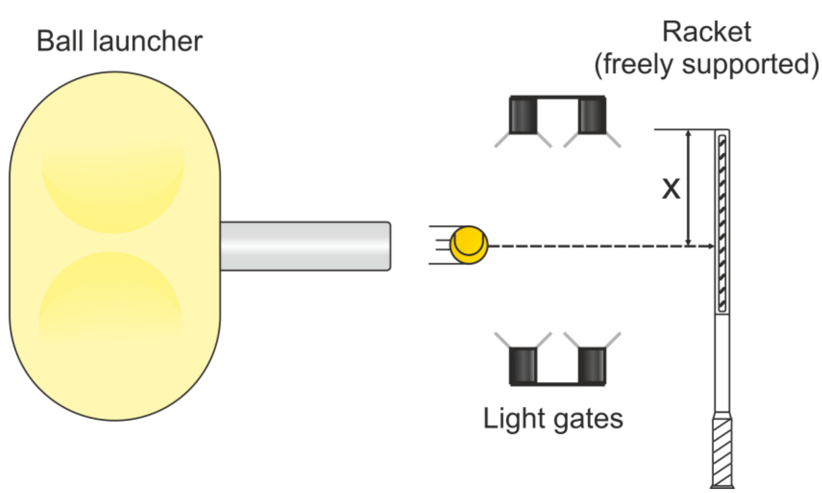

Figure 3 Typical experimental setup for testing impacts normal to the racket face. The racket is typically supported at the tip by a short horizontal pin or stood on its butt, to simulate free-free conditions upon impact. A velocity profile can be obtained by adjusting *x*. As an alternative means of measuring ball velocity, the light gates can be exchanged for a high speed camera. Sampling rates should typically be greater than 100 Hz.

It is often desirable to predict ball rebound velocity for specific impact velocities and locations on the racket face. Recently, Choppin [43] applied a three-dimensional surface fit to experimental data for normal ball/racket impacts at a range of velocities and locations on the long axis. Ball rebound velocities for simulated tennis strokes with different racket angular velocities can be correlated with this technique.

The desire for more realistic impact conditions has led to the development of more sophisticated experimental methodologies. Almost all tennis groundstrokes use racket speed and the angle of the racket face to create ball spin. Post-impact ball spin has been measured in the range of approximately 0 to 350 rad/s for elite players, pre-impact spin values range between 50 and 500 rad/s [7, 23, 24]. During an oblique impact, contact forces change the spin and transverse velocity of the ball (see [32] for a full explanation). Full-constrained rackets (head-clamped) are often used when simulating oblique impacts (Table 1) to simplify the measurement of rebound ball speed, angle and spin and test the string bed in isolation (Figure 4) [32, 36, 37].

Fully constraining the frame does not correspond to realistic player support and impact forces are likely to be significantly higher as the racket cannot recoil. Stereo calibration and high-speed camera techniques provide a means of investigating off-axis and/or oblique impacts on an unconstrained racket – allowing the researcher to measure ball velocity (in three dimensions) and impact location. Allen et al. [33] used this technique to obtain data for oblique spinning impacts on a freely suspended racket, which was used to validate a finite element model. The effect of a player's grip is discussed in more detail in section 5.2.

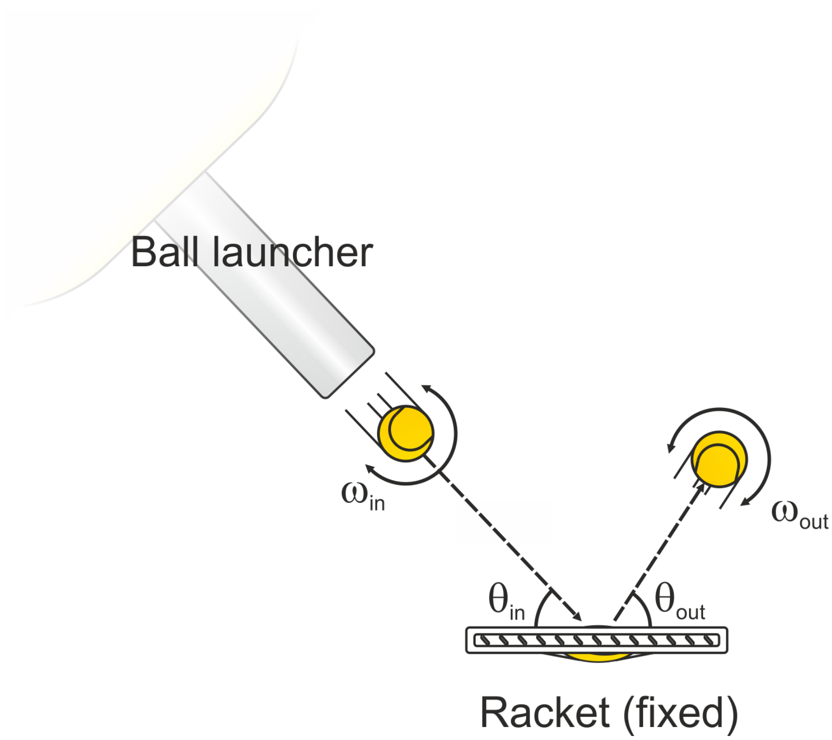

Figure 4 Typical experimental setup for testing the string bed for impacts oblique to the racket face illustrating the spin and angle in/out (ω and θ respectively). A high speed camera positioned with the focal axis perpendicular to the plane of the ball trajectory would be used to measure inbound and rebound velocity, angle and spin. Sampling rates should be greater than 100 Hz.

3.2. Modelling techniques

Mathematical models provide an efficient means of assessing racket performance and they can vary greatly in complexity. In the simplest case, the ball/racket interaction can be simplified to an impact between two point masses, using a fixed value of COR and the principle of conservation of momentum (see [39]). Fixing COR is a simple means of accounting for energy losses in the ball/racket system. The racket can be simplified as a point mass using the concept of effective mass [11].

The effective mass at a distance b from the centre of mass along the longitudinal axis is defined by

$$M_e(b) = \frac{I_{COM} \cdot M}{I_{COM} + Mb^2} \quad [1]$$

The concept of effective mass can also be applied along the racket's offset axis. At a position b along the longitudinal axis, offset by distance a, the effective mass can be defined as

$$M_{ee}(a, b) = \frac{I_p \cdot M_e(b)}{I_p + M_e(b)a^2} \quad [2]$$

where I_p is the polar moment of inertia.

A number of authors have applied Newtonian mechanics to produce one dimensional rigid body models of the ball/racket interaction [43, 50, 51, 53, 56, 57]. These models provide a simple means of predicting how ball rebound speed is affected by changing inertial properties and impact position on the longitudinal axis. They omit any dependence of pre-impact racket speed on inertial properties (i.e. the ability of a player to swing rackets of different swingweights as discussed in section 5.1) and do not allow the effect of frame stiffness to be investigated. Introducing separate segments into a beam model allows the effect of stiffness to be studied [51, 58–60]. Glynn et al., [61] presented a model for simulating non-spinning off-axis normal impacts on a flexible racket.

The most powerful computational impact modelling tool is currently finite element analysis, which to the best of our knowledge is the only technique which has been applied to simulate oblique spinning impacts on an unconstrained racket (e.g. [33]). Due to the nature of finite element modelling, the techniques pioneered by Allen and colleagues can be applied to simulate a variety of racket designs. Finite element simulations offer a wealth of data, such as temporal ball/string bed contact forces, which can contribute to furthering our understanding of impact mechanisms.

Trajectory simulations, combined with racket impact models (or the results of experiments) allow the ball's flight to be predicted and illustrated in the court frame of reference [1, 62, 63]. This extra step in the modelling allows the engineer to not only assess the rebound speed, angle and spin of the ball but also the distance travelled, time taken and impact location on the court. There are a number of comprehensive publications which should be of assistance to readers wishing to develop a model of the trajectory of a tennis ball [64–66].

4. EFFECT OF TENNIS RACKET PARAMETERS ON BALL REBOUND

The challenge for engineers and researchers striving to improve or monitor racket performance is the complex way in which a change in the racket's parameters interacts with the swing of the player, the strings, as well as the impact with the ball. Readers are also referred to articles that have summarised the likely changes in performance, match play statistics, and opinions that are a result of changes in tennis racket design [1, 62, 67–70].

4.1. Frame Stiffness

A frame's stiffness can be increased by using stiffer materials or by changing its geometry. Freely suspended fundamental frequency is often used as an analogue to frame stiffness (see [51]). Haake *et al.* [1] reported frequency values of around 80 to 120 Hz for pre-1970s rackets, with modern rackets in the range of approximately 100 to 180 Hz. The transition from wood (or aluminium) to composite frame materials led to lighter and stiffer rackets. Composites offer high specific modulus and manufacturing versatility, allowing for frames with large cross sections and thin walls [3].

Following an impact with a ball, the racket will recoil and vibrate with associated energy losses of approximately 58-64% [71]. Energy losses associated with internal vibrations of the frame are dependent on impact location (Fig. 1) and stiffness. Energy losses in the ball/racket system increase with impact speed as a result of greater losses in the viscoelastic ball. Predictive modelling techniques (e.g. flexible beam and finite element) have been applied to investigate the effect of frame stiffness for normal impacts on the long axis. Frame stiffness has been shown to have virtually no effect for impacts at or close to the node, as the fundamental mode is not excited [33, 59, 72–74]. Stiffer rackets experience lower energy losses for impacts away from the node, particularly near the tip and in the throat region where effective mass is greatest [33, 59, 72]. Modern frame technology is beneficial for the recreational player as the penalty for hitting away from the centre of the racket is reduced.

Finite element techniques have also been applied to investigate the effect of frame stiffness on oblique impacts with a spinning ball [33, 35]. Allen et al. [35] demonstrated a 9% increase in ball velocity when going from a racket with low structural stiffness (96 Hz) to a very stiff racket (253 Hz), for impacts up to 85 mm from the centre of the string bed. Stiffness had no clear effect on the rebound angle or spin of the ball. For constant inertia, stiffness will not affect a player's ability to swing. However, players may adjust their technique with frame stiffness to compensate for changes in ball rebound or vibrations felt at the hand.

Greater racket stiffness can increase ball rebound speed [58, 75] and accuracy [30]. Shot accuracy is usually defined using the initial angle of ball rebound relative to the intended target. Elite players typically strike the ball close to the node during a ground stroke [7], in order to reduce vibrations felt at the hand or reduce the ball clipping the frame. As a result, stiffness does not have a large effect on ground strokes. The effect of stiffness is greater for serves, as the ball is typically struck away from the node towards the tip. Stiffness interacts with string tension [76, 77], so the player will need to adjust stringing when moving to a stiffer frame.

4.2. String bed

The main string bed parameters which influence performance are stiffness (normal and tangential) and friction. String bed stiffness depends on the string pattern and tension, as well as the diameter and material. Tennis strings are available in a range of materials, traditionally natural gut was favoured but there has been a transition to synthetic materials such as nylon and polyester. Friction falls under two categories, ball/string and inter-string. Friction coefficients are dependent on the material, particularly surface coatings, although they can also be manipulated by applying lubricants or by roughening the surface.

For a normal impact, strain energy is distributed relatively evenly between the string bed and ball [38, 39]. The ball loses around 45% of its stored energy, while only 5% of the strain energy in the string bed is lost (and not transferred back to the ball). Decreasing the stiffness of the string bed (by decreasing string tension or stiffness) marginally increases the rebound velocity of the ball, as a greater proportion of energy is transferred to the more efficient string bed [78]. Goodwill et al. [32] showed normal rebound speed to increase as string tension decreased for oblique impacts in a laboratory experiment, although rebound spin was reported to be independent of string material, diameter and tension. Bower and Cross [79] showed rebound ball speeds to be inversely related to string tension for actual tennis strokes, in line with the laboratory results and theoretical predictions of other authors [54, 78, 80].

The main strings (*parallel to longitudinal axis*) can also deform in a direction parallel to the face of the string bed (lateral), particularly during an oblique impact. The unique, non-interlaced stringing pattern of the ‘Spaghetti racket’ [81], enabled significant lateral deformation of the main strings. The strings would return while the ball was still in contact [82]. The returning movement of the strings acted to increase the spin of the ball, while decreasing its transverse velocity. Recent studies have shown a similar but less pronounced effect can be obtained by reducing the number of cross strings [37, 83] or lubricating the strings [36, 84].

It is difficult to isolate ball-string friction in a physical experiment – to the best of our knowledge no studies have been published in this area. Allen et al. [34] used a finite element model of a freely suspended racket to investigate the effect of ball/string friction. For an inbound angle of 40 degrees, rebound topspin increased by 33% as the coefficient of friction decreased from 0.6 to 0.2. Coefficient of friction had no effect on ball rebound at 20 degrees.

Recent studies have highlighted that changes to the pattern or friction of a string bed can increase rebound topspin. The majority of these studies, however, were limited to full-constrained rackets (Table 1). Different effects have been observed at different impact angles, highlighting the complexity of ball/string interactions during an oblique impact and emphasising the importance of ensuring appropriate impact conditions which correspond to actual tennis strokes. Further work is required before the effect of string bed parameters on a typical tennis stroke are fully understood. A suitable approach would be a holistic laboratory based study comparing the effect of different string bed parameters, for impact conditions which correspond to a tennis stroke.

4.3. Inertial Properties

The inertial properties of a tennis racket are important because of their effect on shot performance and their interaction with player stroke mechanics. Modern rackets are lighter (240 to 380 g) and have a lower moment of inertia about an axis through the grip (swing weight (I_s)) (0.026 to 0.038 kg/m^2) than the wooden rackets of the mid-20th century [1]. The polar moment of inertia (I_p) is the resistance to angular acceleration of the frame about its longitudinal axis and is approximately 20 times smaller than I_s. Polar moments of inertia have remained relatively constant as decreases in racket mass since the 1970s have coincided with increases in head width [1]. The effective mass of an impact location away from the COM of the racket increases with moment of inertia (both I_p & I_s – equations 1 & 2).

Laboratory tests and models often employ the same impact speed with changes in racket inertia. In this simplified scenario the effect of inertia is clear, rebound ball speed increases (to a limit) with effective mass due to an increase in the momentum exchange from racket to ball. The following studies all used models with constant impact speed. Using data from 133 rackets (I_s = 0.026 to 0.038 kg/m^2) Cross and Nathan [72] showed ball rebound speed to increase proportionally with I_s for normal impacts 0.16 m from the tip. Cross [85] showed ball rebound speed increases with I_p for normal off-axis impacts. Allen et al. [35] investigated the effect of racket mass (magnitude and COM position) on oblique impacts with a spinning ball. Ball rebound speed increased by 37% with racket mass, in the range 279 to 418 g, and by 31% as the COM moved from 29.9 to 39.6 cm from the butt. Rebound topspin increased by 23% with mass and 21% with COM position.

Impact simulations have shown an increase in I_s to be beneficial to ball velocity. The work of Haake et al. [1], however, shows a downward trend of I_s over time. Clearly, the moment of inertia of a racket interacts with the player in a way that was not accounted for in most simulation studies. The reduction of racket mass (and moment of inertia) in modern frames may not result in reduced ball velocities because players tend to swing lighter rackets faster [8, 86]. In addition, lower moments of inertia allow for easier changes in trajectory and swing velocity mid-swing.

5. BIOMECHANICAL INTERACTIONS

A complicating factor in understanding the mechanical effects of racket and string parameters on performance is the interaction of the racket with the player. Biomechanical factors of the stroke interact with racket parameters like mass and moment of inertia; they influence the pre-impact racket speed and accuracy the player can generate. The interaction of racket parameters with the player is also complicated because of the mechanical interactions mediated by the grip of the racket. The effectiveness of a tennis stroke is a complex combination of ball speed, spin, and the angle of rebound off the string bed. Research into these complicated problems is limited, many manufacturers rely heavily on player testing of prototypes [87] to ensure that psychometric and biomechanical factors do not interfere with prospective sales. Future research on racket properties should view player-racket interactions as the basis of engineering design.

5.1. Inertial Parameters and Players

The previous section noted that most modern rackets have low I_s values. Some advanced players add lead tape to increase racket mass and I_s. Research has confirmed that advanced players are able to detect differences in I_s of 2.5 percent [88]. Adding mass at the tip has the largest effect on I_s and shifts the centre of mass closer to the middle of the string bed, both of which act to reduce energy lost to translation and increase the speed of ball rebound [89].

When exploring biomechanical interactions with increases in racket mass and I_s, the serve has been studied most. Mitchell et al. [8] studied the serve kinematics of six skilled tennis players using four rackets within the variation of I_s available at that time. Racket speeds at impact (24 to 34 m/s for all participants) were inversely related to I_s. Two participants, however, achieved the highest speed with rackets matching their regular frames. Whiteside et al. [86] reported that a 5 to 10% increase in I_s changed impact locations on the racket face, affected upper extremity angular kinematics and marginally reduced racket speed prior to impact.

Cross and Bower [70] studied planar overarm swing motions of four participants swinging rods with different inertial properties. They also observed decreases in swing speed with increasing implement I_s, as well as interactions of various inertial parameters and swing kinematics. They reported the following relationship for maximum linear speed (V) at a point 60 cm from the end of the handle

$$V = \frac{C}{{I_0}^n} \quad [3]$$

where C is a constant for each participant, I_0 is the moment of inertia of the rod–hand system about an axis through the end of the handle and n was found to be 0.27 when $I_0 > 0.03$ kg•m^2. Bower and Cross [70] claimed that given the mass of a tennis ball and typical impact position on the face, racket masses between 300 and 500 g were near optimal for maximal ball rebound speed. Haake et al [1] showed the mass of modern rackets sit close to the lower end of this range, typically 240 to 380 g.

When adding mass to a racket the immediate effects on stroke performance are difficult to predict – the primary outcomes, racket speed and accuracy, tend to be inversely related. A racket with a higher mass and moment of inertia is more difficult to accelerate in the stroke, but is more effective in transferring momentum to the ball. This relationship should be considered when investigating the effect of racket inertia on ball rebound, as done by Smith and Kensrud [90] when characterising softball bat performance.

Other examples of the interaction of racket mechanical characteristics with player biomechanics are skills test performance measures taken when using rackets of different sizes and masses. Gagen et al., [91] reported that based on the speed and accuracy of developing players' (4 – 10 years old) strokes using different rackets, there tended to be a 'best' racket for each child. It is possible that the combination of many stroke biomechanics, development, and learning parameters means that it will be difficult to optimise racket inertial parameters.

5.2. Grip Effects

The short duration (5 ms) of the impact between a tennis ball and string bed in a stroke [92–94] means that hand forces will have negligible effects on most stroke parameters. Pre-impact grip forces are associated (r^2 = 25 to 36 per cent) with post-impact peak forces and vibrations [95, 96], but are not related to ball rebound speed [97–100], and accuracy [101]. A simulation study confirmed the lack of an effect of grip forces on the speed of ball rebound, but did predict potentially meaningful increases (up to 1 degree) in shot accuracy with high levels of grip axial torque [63]. In summary, tennis players normally need only to grip the racket with enough pressure to control racket motion in the stroke. Given most ball rebound parameters, the racket essentially behaves mechanically at impact more like a freely moving rather than a restrained implement.

The performance of a tennis racket is not only a function of its physical properties but also the manner in which it interacts with the player that wields it. The effect of several racket design variables (stiffness, string bed and inertial properties) has been studied extensively in isolation, and optimising their combined effect would be of particular interest. The interaction between tennis racket design, through effects of the grip and player biomechanics is a promising area of future research.

6. CONCLUSION

Racket properties influence the rebound of the ball in tennis strokes. Rebound ball speed is positively related to racket stiffness and inversely related to string tension. Reducing inter-string contacting forces increases rebound topspin. Racket swingweights in the range 0.030 to 0.0350 kg/m^2 allows for high ball speed and accuracy. The customisation of rackets to individual players would be aided by a development of our understanding of the relationship between moment of inertia about the grip and maximum swing speed.

The effect of racket properties is dependent on the impact conditions, speed, angle, spin, and interactions with the player and stroke biomechanics. The ITF do monitor racket performance but industry standard tests do not exist. Establishing appropriate testing standards would further our understanding and reduce discrepancies between studies. Projecting a ball against an initially stationary racket serves as a suitable test method. However, more emphasis should be placed on data fitting techniques, to reduce uncertainty and allow different strokes to be simulated. To reflect actual strokes, impact velocity should be in the range of ~15 to 40 m/s, inbound ball spin should go up to 500 rad/s and impact angles should be below 35° to the racket face normal. Future research should focus on furthering our knowledge of ball and racket movements during match play to ensure test methods are appropriate and fit for purpose.

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